

# Nondestructive Evaluation (NDE) Techniques Assessment for Graphite/Epoxy (Gr/Ep) Composite Overwrapped Pressure Vessels

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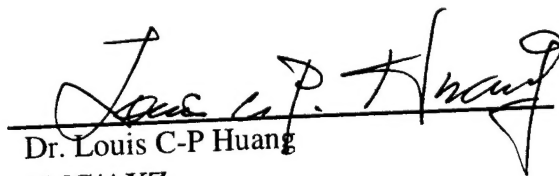
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13. ABSTRACT (Maximum 200 words) <p>NDE methods evaluated included eddy current measurements, ultrasonics, radiography, acoustic emission monitoring, acousto-ultrasonics, and interferometric (e.g., shearography) methods. The major interest was in the detection of damage to COPVs caused by impacts at energy levels that would leave no visible scar on the COPV surface. Each of the above-mentioned NDE methods was assessed with regards to its utility for the detection of impact damage to COPVs and its applicability in the field.</p> <p>Three COPVs were impacted at various energies and then inspected using each of the NDE methods. The results for each method are presented, followed by a summary comparing the advantages and disadvantages.</p> <p>Several NDE techniques were shown to be effective for detecting impact damage sites on graphite/epoxy overwrapped pressure vessels even if the impact energy was below the threshold for creating visible surface damage. These techniques (ultrasound, radiography, thermography, shearography, and eddy current testing) are sensitive because a small dent is left in the liner following the impact.</p> <p>The impact damage detection thresholds for the various NDE techniques employed depend on the size and shape of the vessel. The top characteristics and the internal pressure of the vessel during impact also affect the degree of damage and, hence, the detectability of the impact site. The size of the indication associated with a flaw is also dependent on the technique used. Visual inspection can lead to an underestimate or lack of detection of the damage. For both thermography and shearography, consistent sizing could be accomplished through the use of calibration standards and a consistent test set-up. The ultrasonic and eddy current results are most likely accurate measures of how much of the liner was debonded.</p>				
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## Executive Summary

### Introduction

Task IV of The Enhanced Technology for Composite Overwrapped Pressure Vessels Task Plan was entitled, "Nondestructive Evaluation (NDE) Techniques Assessment." The stated objective of this task was "to determine the ability of the NDE techniques available for use in the production environment and or in the test/assembly facilities to assess flaws and defects in composite overwrapped pressure vessels (COPVs)." NDE methods to be evaluated were to include eddy current measurements, ultrasonics, radiography, acoustic emission monitoring, acousto-ultrasonics, and interferometric (e.g., shearography) methods. A list of specific flaws or defects of interest included "cracks in thin sections in the metal liners; manufacturing defects such as voids or porosity; delaminations, surface cuts, and fiber breaks in the composite overwrap; and debonds at the liner/composite interface." As the program evolved, however, it became apparent that the major interest was in the detection of damage to COPVs caused by impacts at energy levels that would leave no visible scar on the COPV surface. This being so, the Task IV objectives were altered accordingly. Each of the above-mentioned NDE methods was assessed with regards to its utility for the detection of impact damage to COPVs and its applicability in the field.

Included in this report are the results of laboratory tests designed to meet the Task IV objectives. Three COPVs (see table ) were impacted at various energies and then inspected using each of the NDE methods to be evaluated. The results for each method are presented. This is followed by a summary comparing the advantages and disadvantages and detection thresholds of each method.

COPV Specifications

No.	Type	Dia. (cm)	Length (cm)	Liner/Fiber	MEOP (psi)
1.	cylinder	10	23	AL6061/T-1000	3500
2.	cylinder	33	65	AL6061/T-1000	4200
3.	sphere	26.6	NA	AL5083/T-40	5000

### Results/Conclusions

A number of NDE techniques were shown to be effective for detecting impact damage sites on graphite/epoxy (Gr/Ep) overwrapped pressure vessels even if the impact energy was below the threshold for creating visible surface damage. These techniques (ultrasonics, radiography, thermography, shearography, and eddy current testing) are sensitive because a small dent is left in the liner following the impact. Caution must be exercised because repressurization of the COPV can squeeze out the dent and, hence, "erase" the indication. This statement is only partially true for ultrasonics because the ultrasonic signal is also sensitive to damage in the composite. Acoustic emission monitoring is possible because ultrasound is emitted as the matrix and fiber realign during pressurization following an impact. Again, pressurization "erases" the indication. Selection of the most appropriate technique(s) depends on a number of factors including: (1) the specific type (size, shape, material

thicknesses, coatings, etc.) of COPV to be inspected, (2) accessibility constraints during the inspection, and (3) the required sensitivity.

As might be expected, the impact damage detection thresholds for the various NDE techniques employed depend on the size and shape of the vessel. As one might also expect, the impact characteristics and the internal pressure of the vessel during impact also affect the degree of damage and, hence, the detectability of the impact site. The size of the indication associated with a flaw is also dependent on the technique used. For instance, in this study, a 35 J impact on the 10.5-in. sphere gave rise to a ~0.75-in. visual, 2.25-in. thermographic, 2.0-in. shearographic, 1.9-in. eddy current, and 2.0-in. ultrasonic indication. Visual inspection can lead to an underestimate or lack of detection of the damage. The size of a thermographic indication is affected by factors such as the way in which the surface was heated and when after heating the image was acquired. The size of a shearographic indication is affected by the way in which the specimen is loaded during the test. For both thermography and shearography, consistent sizing could be accomplished through the use of calibration standards and a consistent test set-up. The ultrasonic and eddy current results are most likely accurate measures of how much of the liner was debonded. Damage to the overwrap, however, may have extended beyond the debonded region. It should be emphasized, therefore, that the size of the NDE indication may not be consistently related to the size of the region of composite damage since this relation depends on the way in which the site was impacted and its position on the vessel.

Perhaps the most difficult issue associated with the inspection of COPVs is that of determining inspection criteria. One of the reasons that this program was initiated was that some of the data in the literature suggested that impacts to graphite/epoxy overwrapped pressure vessels that left no visible surface indication could still significantly reduce the burst pressure of the vessel. Obviously, what is needed is a correlation between indication size for the inspection technique chosen (and location on the vessel) and the expected reduction in burst pressure. Other subtasks to the Enhanced Technology for Composite Overwrapped Pressure Vessels Program address this issue.



## 1. Background

Composite Overwrapped Pressure Vessels (COPVs) typically consist of thin-walled metallic (or plastic) bottles overwrapped with high strength fibers embedded in a composite matrix, as depicted in Figure 1. Depending on the materials used and type of construction, a COPV can deliver the same performance as an all metal vessel, yet exact only 50–70% of the weight penalty associated with the metal vessel. In some designs, the fibers carry over 80% of the design pressure load for the vessel. The inner bottle (or liner) exists primarily to confine the gas and acts as a mandrel for wrapping of the fibers. COPVs are manufactured in a variety of shapes and sizes. Common fiber materials include graphite, fiberglass, or Kevlar. The liner is often composed of aluminum, stainless steel, or occasionally polypropylene.

COPVs are a potential solution wherever gases must be stored under pressure and the weight of the storage vessel is a concern. Applications have included oxygen packs for firefighters, oxygen storage for commercial aircraft, and fuel storage for transit buses. COPVs have also become standard equipment for energy storage in numerous aerospace applications such as thrusters for station keeping on satellites and fuel tank pressurization for launch vehicles

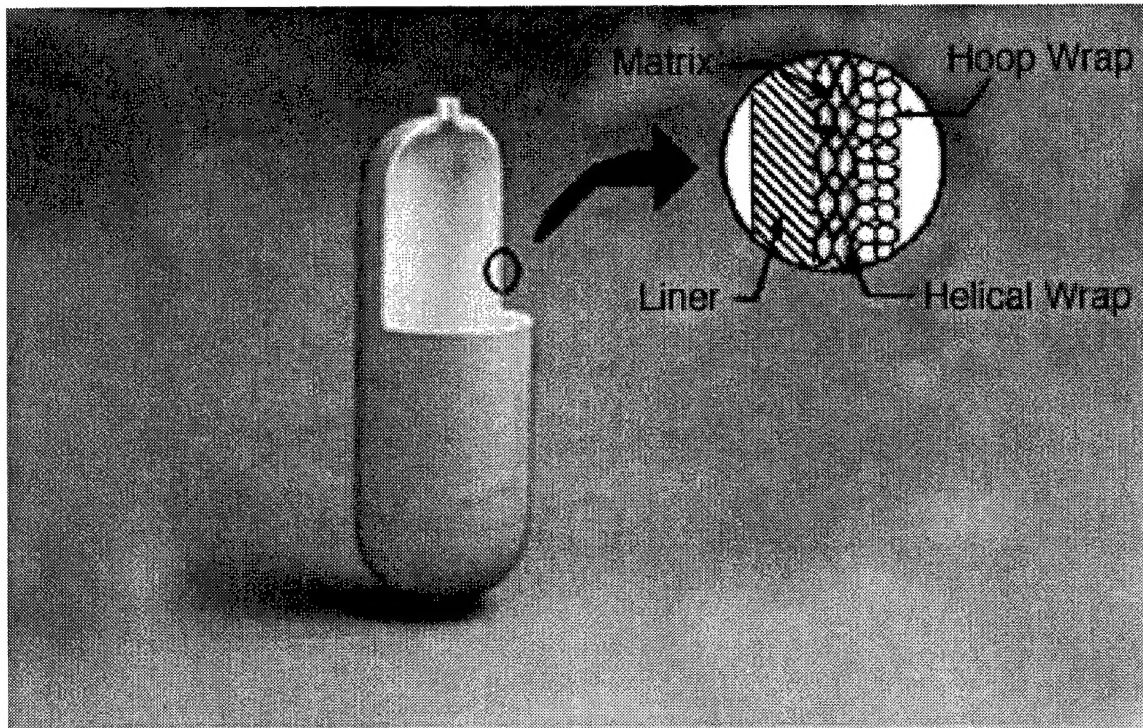


Figure 1. Sectional view of a typical COPV.

Whenever gases are stored under high pressure, the potential for inadvertent sudden release of the gas and the associated stored energy becomes an important safety issue and a possible mission failure mode. In addition, if the stored gas is noxious, explosive, or reactive, even a slow leak becomes a concern. For launch vehicles and satellites, the strong drive to reduce weight has pushed designers to adopt COPVs overwrapped with graphite fibers embedded in an epoxy matrix because this configuration results in the highest strength-to-weight ratio. Unfortunately, this same fiber configuration is more susceptible to impact damage<sup>1,2</sup> than others (e.g., Kevlar epoxy or fiberglass), and, to make matters worse, there is a regime where impacts that damage the overwrap leave no visible scars on the COPV surface.

In order to better assess and reduce the risks associated with using graphite epoxy overwrapped COPVs, a program entitled, "Enhanced Technology for Composite Overwrapped Pressure Vessels," was initiated in 1992. Participants in the program included representatives from NASA, Lockheed Martin Corporation, the US Air Force, The Aerospace Corporation, and General Physics Corporation. The objectives of the program included: "(1) to identify and evaluate critical parameters and procedures of current industry practice in the design, analysis, testing and operation of space flight COPVs such that the safety requirements for already built COPVs can be formulated; (2) to establish detailed material requirements, key manufacturing parameters and quality assurance procedures to enhance safety and reliability of future COPVs, (3) to investigate practical approaches to improve performance and cost effectiveness of COPVs in space systems, and (4) to provide inputs into the revision of MIL-STD-1522A."

To accomplish the aforementioned objectives, the program was broken into nine tasks. Task IV, addressed in this report, was entitled, "Nondestructive Evaluation (NDE) Techniques Assessment." The stated objective of this task was "to determine the ability of the NDE techniques available for use in the production environment and or in the test/assembly facilities to assess flaws and defects in COPVs." NDE methods to be evaluated were to include eddy current measurements, ultrasonics, radiography, acoustic emission monitoring, acousto-ultrasonics, and interferometric (e.g., shearography) methods. A list of specific flaws or defects of interest included "cracks in thin sections in the metal liners; manufacturing defects such as voids or porosity; delaminations, surface cuts, and fiber breaks in the composite overwrap; and debonds at the liner/composite interface." As the program evolved, however, it became apparent that the major interest was in the detection of damage to COPVs caused by impacts at energy levels that would leave no visible scars on the COPV surface. This being so, the Task IV objectives were altered accordingly. Each of the above-mentioned NDE methods was assessed with regards to its utility for the detection of impact damage to COPVs and its applicability in the field.

What follows are the results of laboratory tests designed to meet the Task IV objectives. The COPVs used for the tests and the method by which they were impacted are described. The results from tests using each of the NDE methods to be evaluated are then presented. Finally, a summary compares the advantages and disadvantages and detection thresholds of each method.

Prior to the start of the experimental testing, a comprehensive literature search was undertaken to evaluate the state of COPV inspection techniques. Selected references are included at the end of this report.<sup>3-11</sup> The results of this search showed that the majority of the research efforts had been directed toward the use of acoustic emission (AE) techniques for damage detection. In particular,

work was undertaken to determine the actual burst pressure from the response of the vessel during the manufacturing proof pressure operation.<sup>3</sup> Additional testing was conducted at Lockheed Martin Aerospace (LMA) to determine the effect of various manufacturing parameters to the AE characteristics.<sup>5</sup> Conclusions drawn from much of this work reveal the difficulty in the interpretation of parameter-based AE. Effective AE monitoring requires the use of the new generation of wave-based AE systems. As these systems become available, additional testing will be required to validate the sensitivity of AE to the burst pressure and the manufacturing parameters. Additional research into the use of acousto-ultrasonics did indicate a sensitivity to damage in Kevlar-wrapped vessels. The literature search revealed a general lack of a information on how to inspect the graphite/epoxy COPVs.

## 2. Sample Preparation

Three different COPV designs (Figure 2) of the dimensions and Maximum Expected Operating Pressure (MEOP) tabulated in Table 1 were used for this impact damage detection study. Both cylindrical designs consisted of a 6061-T62 aluminum liner overwrapped with T-1000 graphite fibers in epoxy resin. For the smaller cylinder, the minimum liner wall and overwrap thicknesses were approximately 0.08 mm and 1.6 mm, respectively. The larger cylinder had minimum liner and overwrap thicknesses of approximately 1.0 mm and 3.8 mm, respectively. The spherical vessel consisted of two 5083 aluminum alloy hemispheres welded at the equator. The liner was then overwrapped with a T-40 fiber in an epoxy resin. The minimum liner and overwrap thicknesses for this vessel were approximately 1.3 mm and 4.6 mm, respectively.

The vessels described in Table 1 were impacted with a pendulum type impactor to simulate in-service impact damage. After each impact, the vessels were inspected using selected NDE methods to determine approximate detection thresholds. The impact system, shown in Figure 3, consisted of a 2.2-kg rod suspended from four guy wires. A steel tup of a desired geometry could then be fitted to the end of the rod to create a variety of impact conditions. For this investigation, two spherical tups with

Table 1. COPV specifications

No.	Type	Dia. (cm)	Length (cm)	Liner/Fiber	MEOP (psi)
1.	cylinder	10	23	AL6061/T-1000	3500
2.	cylinder	33	65	AL6061/T-1000	4200
3.	sphere	26.6	NA	AL5083/T-40	5000

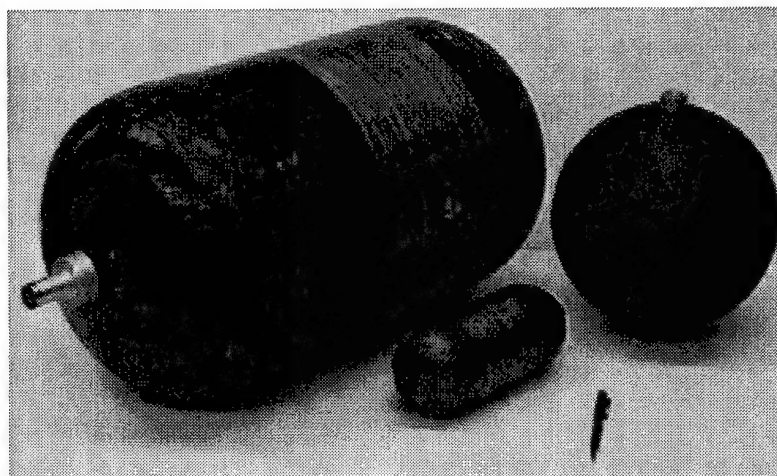


Figure 2. COPVs used in impact damage detection study. The characteristics of these vessels are tabulated in Table 1.

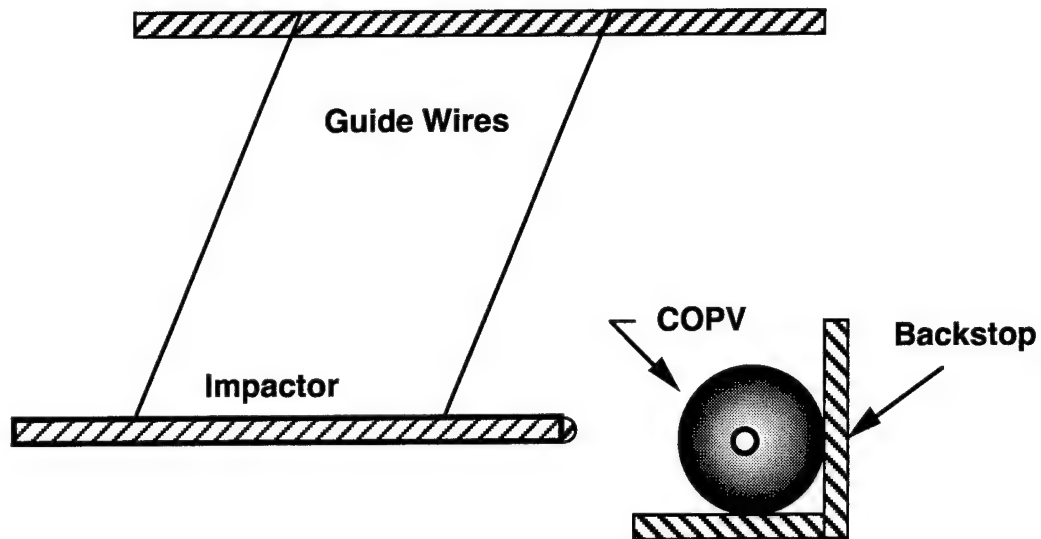


Figure 3. Schematic representation of impactor apparatus.

diameters of 25 mm and 12 mm were used in the testing. The drop-height of the tup could be adjusted to vary the energy of each impact. Using this test system, the COPVs were subjected to impacts ranging in energy from 2 J to 50 J. Additional tests were performed to examine the effects of dropping COPVs a distance of 1 m onto a concrete floor.

### 3. Technique Survey Results

#### 3.1 Visual Inspection

Perhaps the easiest method for inspecting COPVs for impact damage is to perform a visual inspection. The outside of the vessel can be examined for signs of fiber damage with the unaided eye or with magnification loupes. The use of dye penetrants (or an alcohol wipe) can sometimes be used to accentuate indications. The inside liner of the vessel can be inspected for corrosion, cracks, and/or dents through use of a borescope. Obviously, these techniques are hampered by any circumstances that limit visual access to the surfaces in question and by the poor surface contrast that typifies Gr/Ep composites. Visual images of a 35-joule impact site on the spherical test COPV are presented in Figure 4.

As can be noted from Figure 4a, the outside Gr/Ep surface of the COPV exhibited little, if any, indication of the impact. However, Figure 4b reveals that on the inside liner surface a small dent is very apparent. One can surmise, therefore, that the impact damage at this energy level evolves in the manner depicted in Figure 5; the composite overwrap flexes into the metallic liner to accommodate the impact and then returns to its pre-impact position. The liner, on the other hand, is left dented and locally unbonded from the overwrap. It thus should be strongly noted that a visual inspection of the exterior of the COPV will not serve to detect this type of damage. It should also be noted that if the impact has weakened the composite (broken fibers etc.), there is no obvious visual sign. The presence of the dent in the liner is critical for obtaining satisfactory results for a number of the impact damage detection techniques presented in the balance of this report. This is an important observation.

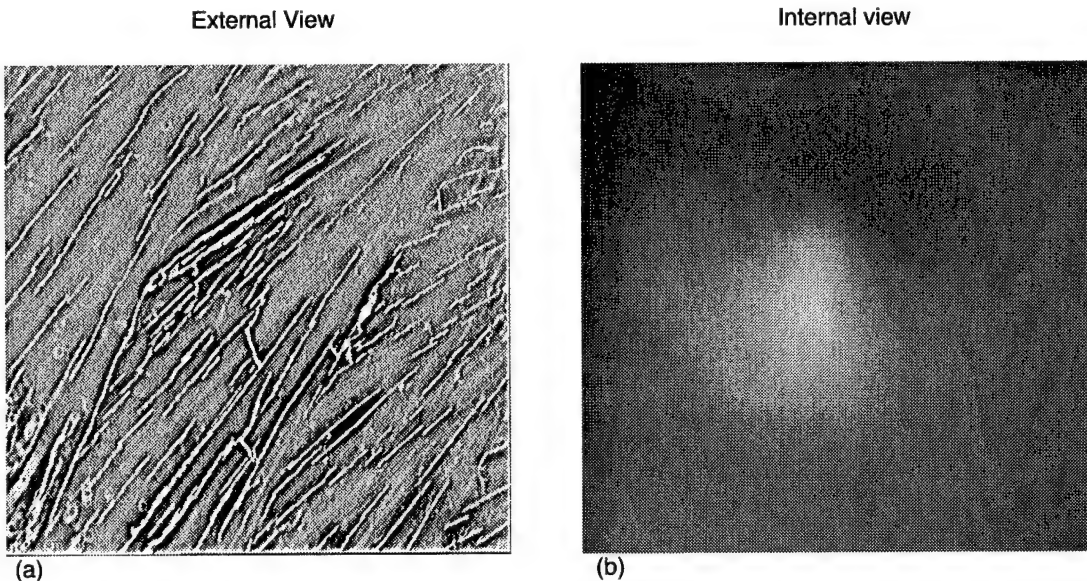


Figure 4. Visual indications of a 35-J impact damage site on spherical vessel. For the external view, dye penetrant was used to enhance the image.

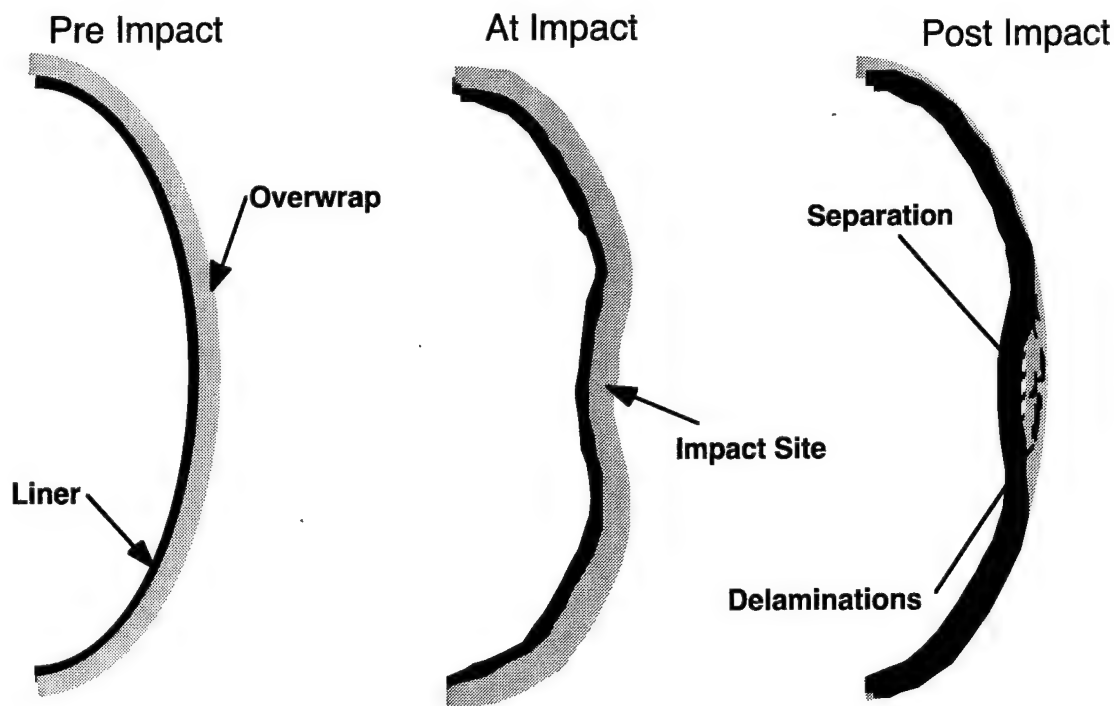


Figure 5. Cross-sectional view of the impact damage event.

It was also noted during this study that, in some instances, repressurization of an impacted COPV caused the dent to disappear. In other words, for some inspection techniques, the effects of an impact can be erased by pressurizing the bottle!

### 3.2 Ultrasonic Testing

As one might expect, the type of damage described in Figure 5 can be detected using a handheld pulse-echo ultrasonic probe on the outside surface of the COPV. In the region of impact, the ultrasonic pulse returns early because the sound cannot bridge the gap to the dented liner. Damage within the composite results in a decrease in signal amplitude, which can also be detected in some circumstances. A comparison of a typical waveform recorded on an impact site and on an adjacent nominal site is presented in Figure 6.

To eliminate variances associated with the hand coupling and positioning of transducers, the impacted COPVs were inspected using both a through-transmission and a pulse-echo ultrasonic technique. In both instances, the COPVs were immersed in and filled with water. For the through-transmission technique, a sound pulse generated by one transducer was received by a second after passing completely through the COPV. For the pulse-echo technique, a reflection rod was inserted into the center of the COPV. In both instances, the amplitude of the 5-MHz pulse was recorded as a function of position after passing through the wall(s) of the COPV. The data revealed that ultrasound can be used to detect non-visible impact damage in COPVs. A C-scan representation of a 10 cm x 23 cm COPV after a 10-J impact is presented in Figure 7. Though the impact left no visible indication on the surface of the COPV, the impact site is clearly visible in the central section of the C-scan image.



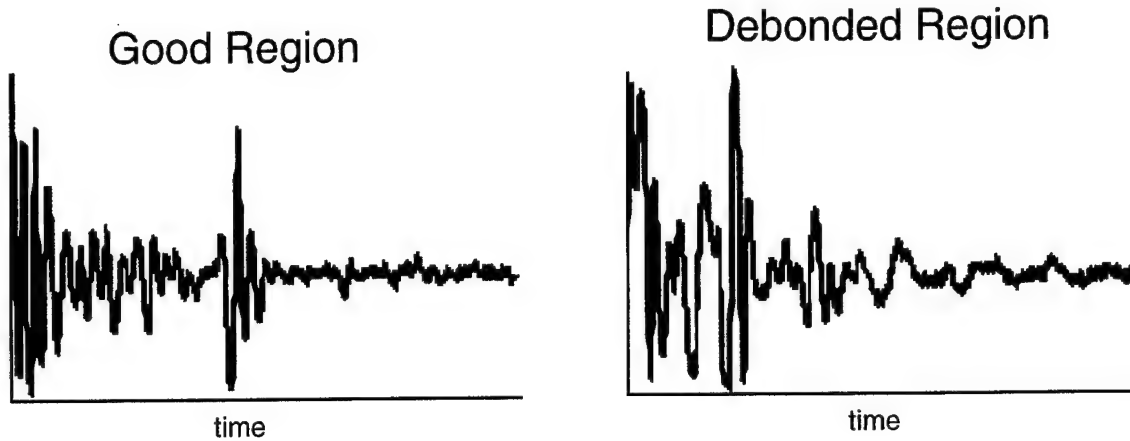


Figure 6. Pulse echo A-scans from a good and debonded region of an impacted COPV. The measurements were made using a 10-MHz transducer and Ultragel II™ couplant. Note the strong (early) response from the backside of the overwrap in the debonded region.

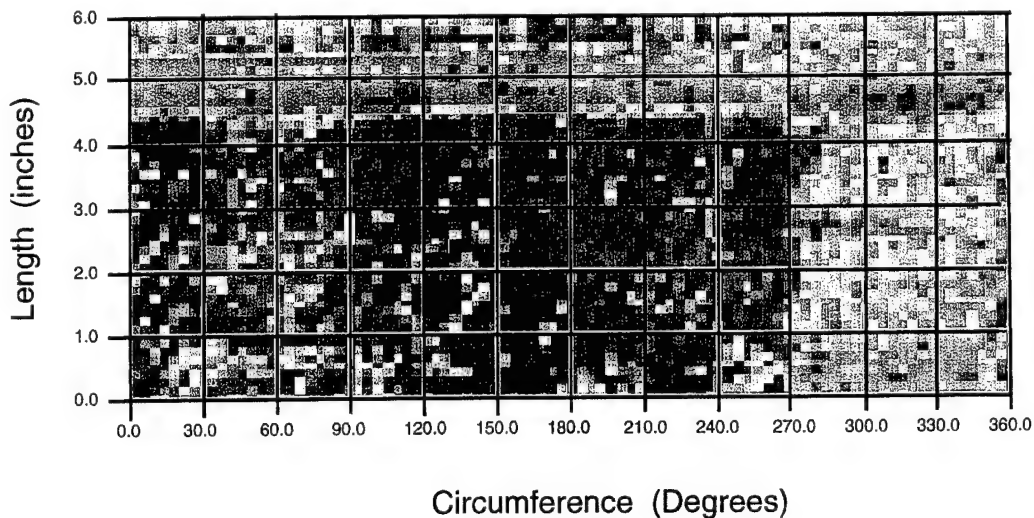


Figure 7. C-scan image of a 10 cm x 23 cm COPV after a 10-J impact. The impact site gives rise to an obvious, somewhat circular indication centered at about (125°, 1.5 in). The rectangular indication on the right was due to a label affixed to the bottle. The stripe along the top of the scan was due to the curved edge of the bottle.

Unfortunately, immersion of flight hardware will most likely not be tolerated. It should be noted that performing a reliable handheld ultrasonic scan of the entire outside of a suspect COPV might be difficult if access to the vessel is limited or if the outside surface has a rough texture. In addition, a liquid or gel might be required to couple the sound into the vessel.



### 3.3 Shearography

Electronic shearography is a non-contacting, interferometric method for measuring changes in the out-of-plane slope of a surface. Using charge-coupled device (CCD) cameras and computer processing capabilities, shearography can be applied in a variety of NDE applications. The application of shearography to COPVs requires that an initial image of the vessel be acquired and stored in the digital memory of the computer. After storing the initial image, a small load is applied to the COPV. Best results were found by pressurizing the COPV to some value less than 50 psi. A second image of the loaded or slightly deformed vessel is acquired and subtracted from the initial image. The result is a family of high-contrast interference fringes indicative of the deformations due to the pressure differential. Impacts to vessels can cause subtle changes in load carrying characteristics and, hence, the contour of the vessel that are effectively detected using shearography. Results for a 35-J, 25-mm tup impact to the 33 x 65 cm cylindrical COPV are presented in Figure 8. Note the typical "butterfly" indication centered on the impact site that resulted upon a 25 psi pressurization of the vessel.

The shearographic technique was found to be particularly effective for detecting impacts in the spherical COPV because of the relatively uniform stress field, as shown in Figures 9a and 9b. The fringes presented in Figure 9a represent the nominal deformations of a spherical COPV under a 40-psi

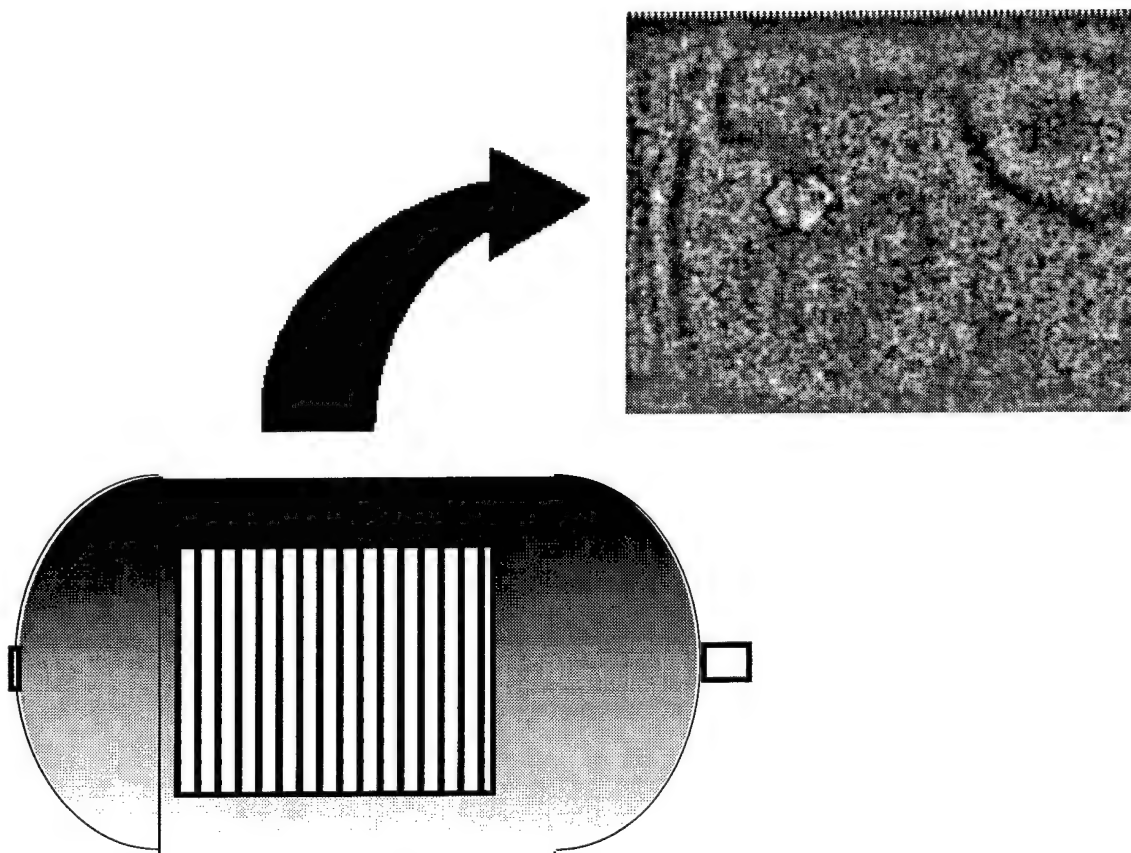


Figure 8. Shearographic image of 35-J, 25-mm tup impacted cylindrical COPV.

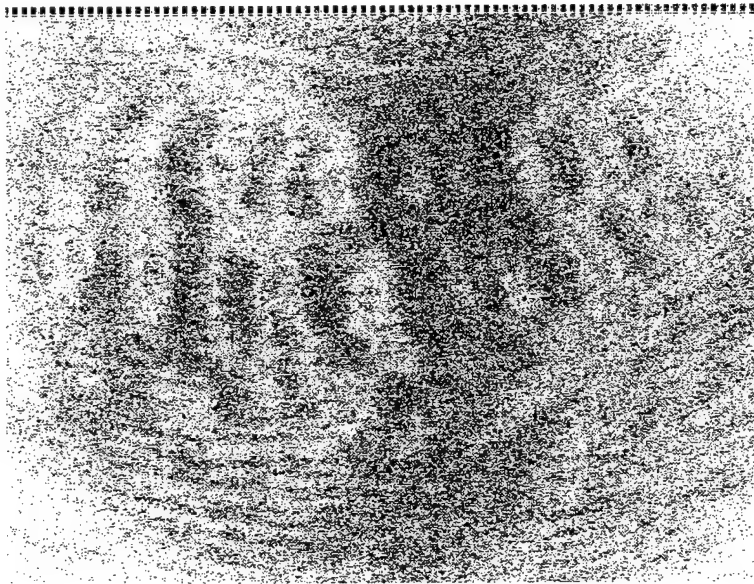


Figure 9a. Initial shearographic image of the spherical COPV using a 40-psi pressure differential.

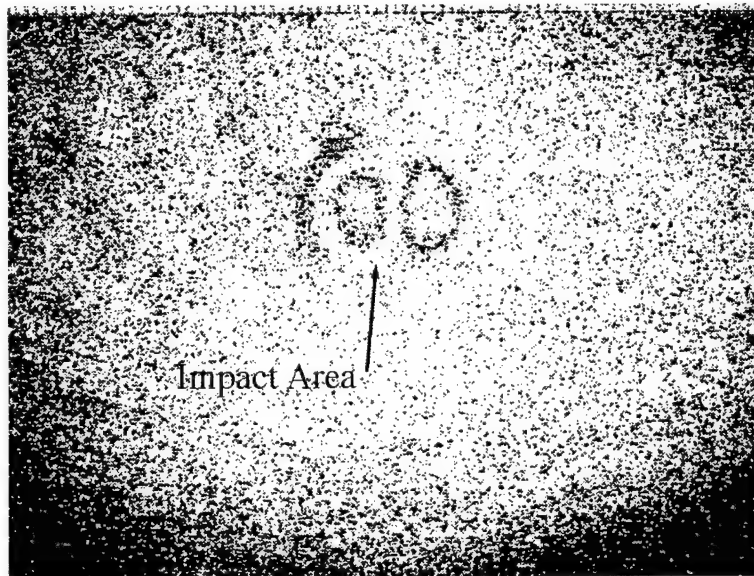


Figure 9b. Post-impact shearographic image of the spherical COPV following a 20-J impact with a 25-mm diameter tup. A 40-psi pressure differential was employed to create the image.

charge. These fringes can be contrasted with the fringes in Figure 9b that clearly indicate the location of a 20-J impact where a 25-mm tup was employed. It should be noted that shearography is a dynamic process in that one can see the indications grow in as the load is applied. This has the effect of making the indications considerably more apparent than is evident from the still images presented. A serious drawback to the use of shearography in this application is the need for a matte surface to

scatter the laser creating the necessary speckle pattern. During testing, the vessels in this report were prepared using either a stripable paint or a spray powder. For installed flight hardware, such an approach would, most-likely, not be tolerated.

### **3.4 Radiography**

The materials and thicknesses associated with typical COPVs provide little impediment to the passage of X-rays of standard inspection energies. However, detection of an impact site requires a tangential shot that manifests the dent in the liner. Total inspection of a COPV would require, at minimum, a number of tangential shots about the circumference using film or a real-time scanner. Computer-aided tomography could also be employed. This may prove reasonable prior to and after COPV shipment, but impractical once the COPV has been installed.

### **3.5 Thermography**

Thermography is a technique for measuring the surface temperature of an object based on its emission of infrared (IR) radiation. Using an IR camera, the complete temperature profile of a target can be recorded at video frame rates (30 Hz). Variations in the surface temperature profile can occur as a result of internal discontinuities or flaws within the structure. Flaws that produce localized variations in the thermal properties of a composite, such as delaminations or matrix porosity, can often be easily detected via thermography.

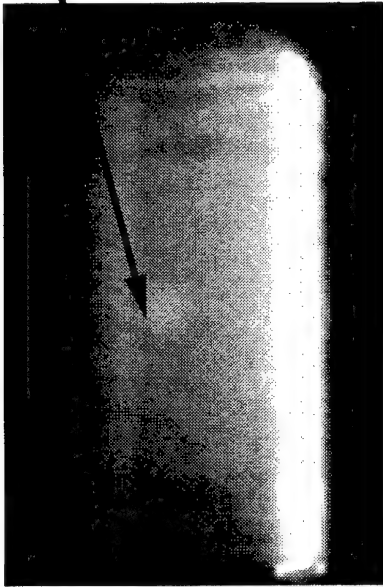
As already mentioned, one possible consequence of an impact to a COPV is the creation of a disbond between the liner and overwrap at the impact site. One would expect a disbonded or bruised area at the interface between the metallic liner and the Gr/Ep overwrap to have a significantly higher thermal impedance than an undamaged area. An increase in the thermal impedance translates into higher surface temperatures when the COPV is exposed to a transient heat source. The locations of surface hot spots can then be mapped using an IR camera. Evaluation of IR data showed bruised areas to be as much as 2°C hotter than surrounding areas shortly after transient heating with a quartz lamp. Images obtained during the thermographic inspection of the 10 cm x 23 cm cylindrical COPV with both 15-J and 20-J impact sites are presented in Figure 10. Both impacts resulted in thermal indications with similar dimensions. The 20-J impact, however, shows the larger temperature differential between the bruised and nominal areas of the COPV.

The successful application of thermographic techniques can be affected by the structure of the vessel. It was noted that impacts of less than 45 J gave rise to clear thermographic indications for the spherical vessel included in this study (Figure 11). It might also be noted that similar tests were conducted on several spherical vessels not included in this report, and that 50-J impact sites were not detectable. These vessels had slightly thicker overwraps and/or liners.

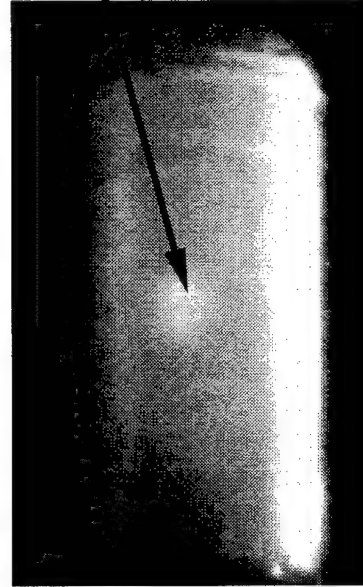
### **3.6 Eddy Current Testing**

Eddy current techniques are commonly used in the inspection of metal parts for the detection of surface and near-surface anomalies. They are also used for measuring coating thicknesses and sorting metal materials. While the graphite fibers in the overwrap are conductive, they are essentially transparent to the eddy current probes at standard inspection frequencies (less than MHz). Within the

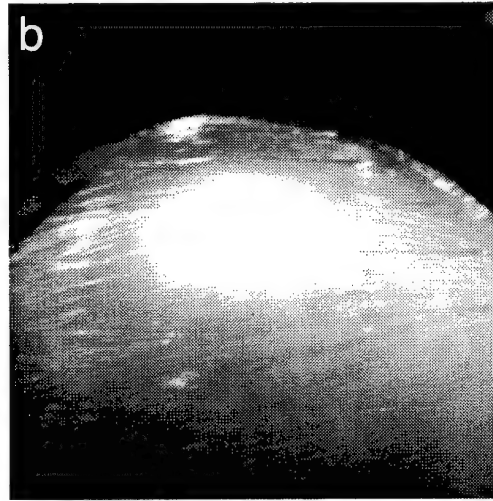
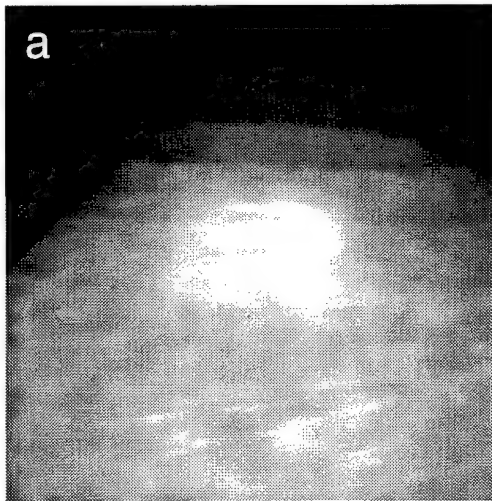
**13 J impact using a 25mm tup**



**20 J impact using a 25mm tup**



**Figure 10.** Comparison of thermographic indications on a 10 X 23 cm COPV following distinct 13-J and 20-J impacts.



**Figure 11.** Thermographic image of a 45-J impact site on the spherical COPV. These images were obtained using an Amber Radiance 1 IR camera (3–5  $\mu\text{m}$ ). The image labeled (a) was acquired ~1 s after the surface was flashed with a high-intensity flash lamp. The image labeled (b) was acquired ~5 s after the surface was warmed with a quartz heat lamp.

COPV structure, the overwrap acts as a spacer between the probe and the metallic liner. Eddy currents, which are very sensitive to the gap between the probe and the liner, can be used to detect the impact-induced dents in the liner. A sample image is presented in Figure 12.

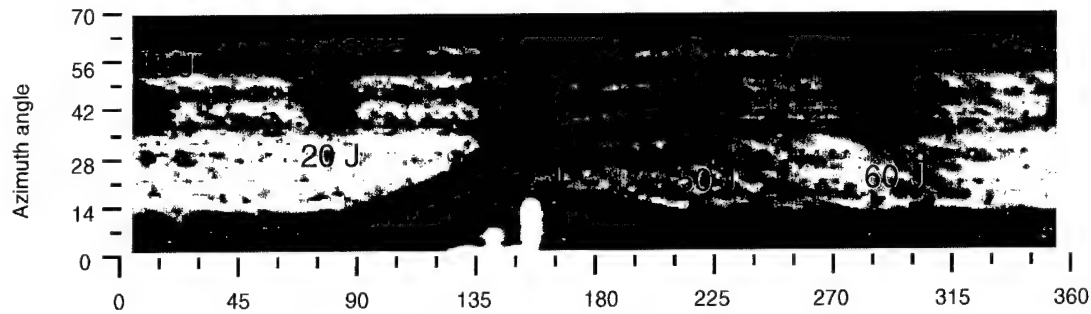


Figure 12. Eddy current image of the spherical COPV with impact sites as labeled. This image was produced with a 75-kHz probe. The finger shape indications near the bottom center of the image are calibration markers placed on the specimen surface.

With this technique, the probes, consisting basically of RF coils, are dry and do not necessarily even have to contact the surface. The penetration depth of the inspection is determined by the probe frequency.

### 3.7 Acoustic Emission Monitoring

Loaded structures typically produce sound as the materials and components within the structure respond to a load. One can monitor these sounds, which typically find their origin in matrix cracking or even fiber breakage, and draw conclusions regarding defect propagation. Acoustic Emission (AE) monitoring is a method for evaluating the structural integrity of a system based on the generation of sound during loading of the structure.

For this investigation, an array of six AE sensors were used to record the acoustic activity of a vessel during pressurization. These transducers were coupled to the COPV with an ultrasonic couplant. COPVs exhibit the Kaiser Effect,<sup>12</sup> which implies that once a structure has experienced a stress level, no new AE will occur again until that stress level has been exceeded, unless, of course, the structure has been damaged before being repressurized. To detect impact damage, the COPVs were subjected to an initial AE screening, and then pressurized again after being subjected to an impact. Changes in the acoustic activity were noted with the COPVs exhibiting significantly more AE events after impacts that exceeded a particular energy threshold. The energy threshold required for AE monitoring to detect an impact varied significantly between vessel types, ranging from 10 J for the small cylindrical COPV to over 20 J for the larger cylindrical vessel. Figure 13 demonstrates the change in AE activity that occurred after a 35-J impact on the 10 x 23 cm cylindrical COPV. In Figure 13a, little AE activity is noted since no damage to the vessel occurred between the original manufacturer's proof pressurization and the AE screening test. Figure 13b reveals a significant increase in AE—clearly indicating a change in the COPV structure as a result of the impact. AE monitoring, however, does not provide a quantitative means for ascertaining the severity of the impact damage. Instead, AE methods appear to offer excellent potential as an impact screening technique. The AE system employed in this study was fairly rudimentary, allowing only for the capture and analysis of several parameters that characterize the acoustic emissions. Emerging technologies that permit a modal analysis of the captured waveforms offer potential for significant improvements in the impact screening process.

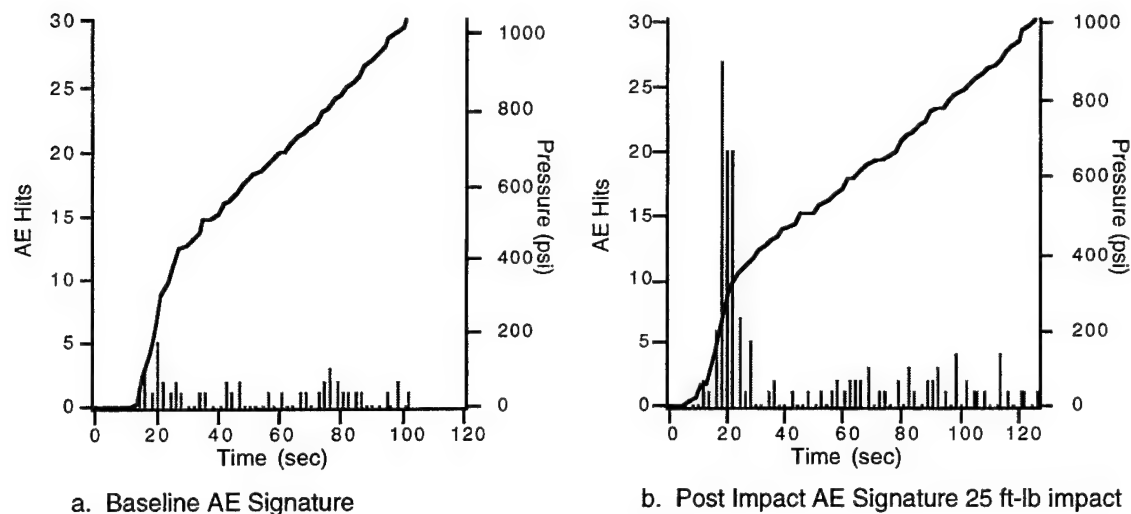


Figure 13. Acoustic emission data for for the 10 X 23 cm cylindrical COPV (a) before and (b) after a 35-J impact.

### 3.8 Other Techniques

A number of other techniques were evaluated during this program, including a microwave technique and acousto-ultrasonics. Microwaves were not effective. They were unable to penetrate the graphite/epoxy, which is a conductive medium. The acousto-ultrasonic techniques mentioned in the literature were found to offer little advantage over standard ultrasonic techniques used for detecting delaminations.

#### 4. General Observations

As might be expected, the impact damage detection thresholds for the various NDE techniques employed depend on the size and shape of the vessel. A comparison of the visual, thermographic, and shearographic results for the large cylindrical vessel and the spherical vessel used in this study is presented in Table 2. For these results, the 25-mm tup was employed, and the COPVs were impacted while unpressurized. As one might also expect, the tup characteristics and the internal pressure of the vessel during impact also affect the degree of damage and, hence, the detectability of the impact site.

The size of the indication associated with a flaw is also dependent on the technique employed. For instance, in this study, a 35-J impact on the 10.5-in. sphere gave rise to a ~0.75-in. visual, 2.25-in. thermographic, 2.0-in. shearographic, 1.9-in. eddy current, and 2.0-in ultrasonic indication. As has already been noted, visual inspection can lead to an underestimate of the damage. The size of a thermographic indication is affected by factors such as the way in which the surface was heated and when after heating the image was acquired. The size of a shearographic indication is affected by the way in which the specimen is loaded during the test. For both thermography and shearography, consistent sizing could be accomplished through the use of calibration standards and a consistent test set-up. The ultrasonic and eddy current results are most likely accurate measures of how much of the liner was debonded. Damage to the overwrap, however, may have extended beyond the debonded region. It should be emphasized, therefore, that the size of the NDE indication may not be consistently related to the size of the region of composite damage because this relation depends on the way in which the site was impacted and its position on the vessel.

Table 2. Comparison of Selected Impact Damage Detection Thresholds

Vessel	Visual	Thermography	Shearography
Large Cylindrical COPV	40-47 J	27-34 J	20-27 J
Spherical COPV	27 J	13 - 20 J	13-20 J



## 5. Summary/Conclusions

A number of NDE techniques have been shown to be effective for detecting impact damage sites on graphite/epoxy overwrapped pressure vessels even if the impact energy was below the threshold for creating visible surface damage. A number of these techniques (ultrasound, radiography, thermography, shearography, and eddy current testing) are sensitive because a small dent is left in the liner following the impact. Caution must be exercised because repressurization of the COPV can squeeze out the dent and, hence, "erase" the indication. This statement is only partially true for ultrasonics because the ultrasonic signal is also influenced by damage in the composite overwrap. Acoustic emission monitoring is possible because ultrasound is emitted as the matrix and fiber realigns during pressurization following an impact. Again, pressurization "erases" the indication (in AE terms, this is referred to as the Kaiser Effect).<sup>12</sup> Selection of the most appropriate technique(s) depends on a number of factors including: (1) the specific type (size, shape, material thicknesses, coatings, etc.) of COPV to be inspected, (2) accessibility constraints during the inspection, and (3) the required sensitivity.

A guide for selecting an appropriate technique is presented in Figure 14. The assessments provided in this figure are the rough opinion of the authors and are by no means indisputable. "Whole Field"

	Whole Field	Flaw Characterization	Inspection Time	Simplicity	Data Evaluation	Sensitivity	COPV Preparation	Field Use
Acoustic Emission	○	◐	●	◐	○	○	◐	●
Acousto-Ultrasonics	○	○	◐	○	○	○	◐	○
Eddy Currents	○	◐	◐	●	◐	◐	●	●
Interferometry	●	◐	●	◐	◐	◐	○	◐
Ultrasonics	○	◐	◐	●	◐	◐	●	●
Radiography	○	○	◐	◐	◐	○	●	○
Thermography	●	◐	●	●	◐	◐	●	●

Figure 14. A summary of the features of various NDE techniques for the inspection of graphite epoxy overwrapped pressure vessels.



relates to how the data is taken—point by point as in a scan vs. a whole field as in a grabbed image. “Flaw Characterization” is an assessment of how well the flaw is characterized (sized). “COPV Preparation” includes what must be done to the COPV to inspect it (coat the surface, etc.). “Field Use” relates to how field deployable the inspection technique is.

Perhaps the most difficult issue associated with the inspection of COPVs is that of determining inspection criteria. One of the reasons that this program was initiated was that some of the data in the literature suggested that impacts to graphite/epoxy overwrapped pressure vessels that left no visible surface indication could still significantly reduce the burst pressure of the vessel. Obviously, what is needed is a correlation between indication size for the inspection technique chosen (and location on the vessel) and the expected reduction in burst pressure. Other subtasks to the Enhanced Technology for Composite Overwrapped Pressure Vessels Program addressed this issue.

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